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Basin and petroleum system modeling of the Cretaceous and Jurassic source rocks of the gas and oil reservoirs in Darquain field, south west Iran

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A B S T R A C T

In south west Iran, in the Abadan Plain, there are several giant gas and oil reserves in Jurassic and Cretaceous carbonates, such as Darquain, where there are excellent source rocks in the Early Cretaceous and Jurassic successions. In present study, petroleum generation and migration from these source rocks were evaluated. Maturity state of organic matter was determined with Organic petrography and results were used for calibration of thermal model. Basin modeling was used for investigation of petroleum generation and migration history. Burial history and 3D thermal model were constructed for the study area using Temis suite and Genex software. Modeling shows source rocks of Jurassic, such as Sargelu and Neyriz are in gas maturity state, oil generation phase passed before Cenozoic. It appears that gas from Jurassic source rocks accumulated in Najmeh and did not reach to Cretaceous Fahliyan reservoir. Cretaceous reservoir in Fahliyan Formation has been charged by the Garau Formation. This source rock reached to oil window in Early Cretaceous time and began hydrocarbon expulsion at the end of Cretaceous when the Darquain structure formed. Migration paths of hydrocarbons shifted from NE to SW direction about 11 Ma in response to changes in regional structural dip contemporary with the Zagros Orogeny. Modeling results indicate that the quantity of gas and oil generated in the kitchen area was more than the reservoirs' capacity. Therefore, the surplus hydrocarbon could have migrated laterally out of reservoir area.

1. Introduction

There are several giant hydrocarbon reservoirs in Abadan Plain, south west Iran, in Jurassic and Cretaceous carbonates (Saadatinejad and Sarkarinejad, 2011) (Fig. 1). The Darquain field is in central part of the Abadan Plain and contains excellent source rocks such as the Early Cretaceous Garau and Middle Jurassic Sargelu Formations (Zeinalzadeh et al., Under Review) (Fig. 2). Gas reserve is present in the Jurassic Najmeh and Sargelu Formations, while oil in the Cretaceous Fahliyan and Ilam Formations.

The Jurassic gas and Cretaceous oil reserves were separated by thick evaporitic sediments of the Gotnia Formation that act as a seal for underling gas reservoirs. Shally sequences of Gadvan Formation act as a seal for the Fahliyan Formation. The goal of this study is to investigate gas and oil generation and migration from source rocks in Darquain structure by using basin modeling tools (1D, 2D and 3D) that can help in a better understanding the petroleum systems of the region. Organic petrography was used for calibration of model.

2. Regional geology

The Abadan Plain is located in south west Iran and is surrounded by the Dezful Embayment, Persian Gulf and Iran–Iraq boundary (Fig. 1). It is a part of Mesopotamian Basin and its structural features are different from the Dezful Embayment. The anticlines in the Abadan Plain are N–S oriented that are different from usual NW–SE trending structures in the Zagros. It is covered by recent alluvial deposits with no outcrops (Saadatinejad and Sarkarinejad, 2011). Abadan Plain source rocks are not well known and it is

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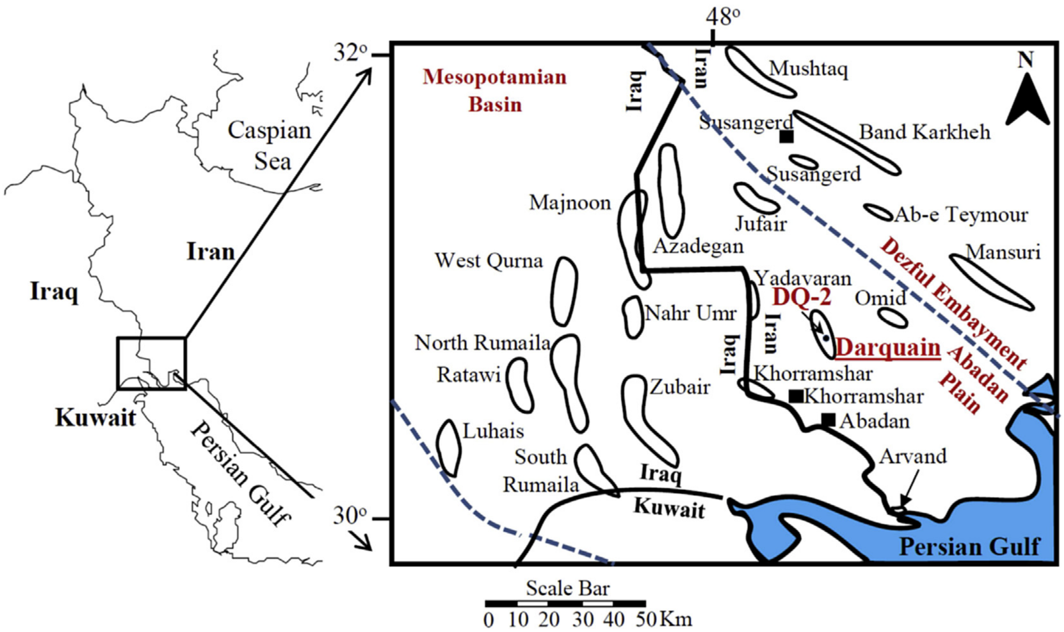

Fig. 1. Location map of the Darquain field and Darquain Well #2 (DQ-2) (Based on Abeed et al., 2012; Bordenave and Hegre, 2010).

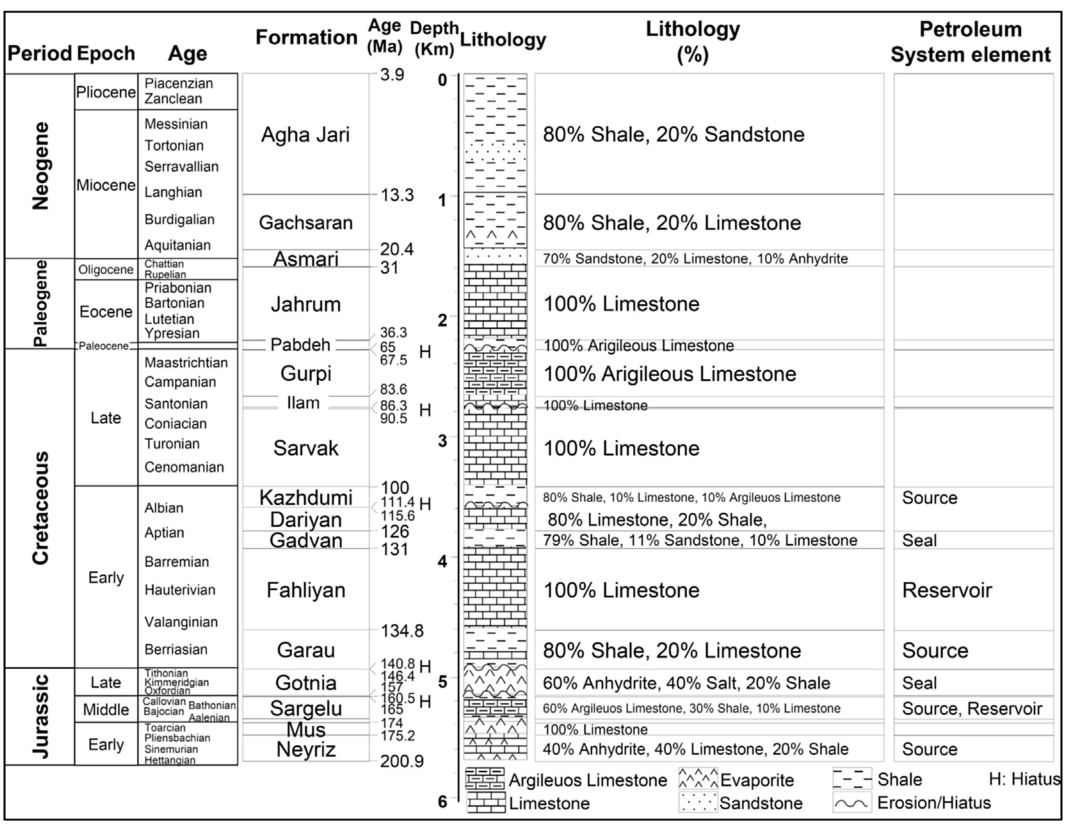

Fig. 2. Stratigraphic column of Darquain Field (Data from unpublished geological completion report of Darquain wells, absolute age is based on Walker et al. (2013)).

thought that this area may have acted as a kitchen area for the Cretaceous reservoirs of Kuwait (Derks et al., 2012; Murris, 1980). Prior to the Zagros folding, in a scenario hydrocarbon could have migrated along low angle ramps from the study area toward paleo high such as Southern Iraq and Kuwait (Bordenave and Hegre, 2005).

The main source rock of the Dezful Embayment, Kazhdumi Formation, is extended into the study area as a good source;

however, there are also excellent source rocks in Early Cretaceous and Jurassic succession in this region (Garau and Najmeh/Sargelu Formation respectively) (Zeinalzadeh et al., Under Review). Jurassic petroleum source rocks, Najmeh and Sargelu Formations, are composed of organic rich argillaceous limestone and shale. Also, these formations are gas reservoirs with abnormal pressure up to 11,261 psi (Well completion report). The seal rock is evaporitic sediments (salt and anhydrite) of the Gotnia Formation (Fig. 2).

The oil reservoir of the Darquain is the Fahliyan Formation that is composed mainly of Limestone and capped by shelly sequence of the Gadvan Formation (Fig. 2). The Late Cretaceous carbonate of Ilam Formation is a minor oil reservoir and it is under development in Darquain.

The Darquain anticline is a broad and gentle structure known as dome or anticline. This structure has four closures in the Jurassic and Cretaceous intervals but no closure is present in the shallower Oligocene-Miocene stratigraphic intervals such as Asmari Formation. It has formed as a result of Cretaceous basement tectonic activity and has been slightly reactivated during the Zagros Orogeny in Late Cenozoic (Abdollahie Fard et al., 2006; Sattarzadeh et al., 1999; Soleimany and Sàbat, 2010). Also it could be related to salt pillowing along Hercynian faults which were reactivated during the Mid Cretaceous time (Bordenave and Hegre, 2005).

There was no active tectonic movement in Abadan Plain (Soleimany and Sàbat, 2010) which led to significant erosion events in Jurassic to recent layers. There was a passive margin setting during Mesozoic to Cenozoic time (Piryaei et al., 2011); that ended to foredeep basin during Neogene time (Navabpour and Barrier, 2012; Pirouz et al., 2011). Low erosion also reported in basin modeling of Mesopotamian basin in south Iraq (Abeed et al., 2013; Pitman et al., 2004). In contrast, in Zagros fold-thrust belt, erosion reached up to 1500 and 2000 m (Aldega et al., 2014; Bordenave and Hegre, 2005; Pitman et al., 2004).

3. Methods and materials

3.1. Basin modeling

In this study, basin modeling software programs Temis suite and Genex, developed by French Institute of Petroleum (IFP), were used for modeling and interpreting hydrocarbon generation, migration and accumulation histories. Burial histories of 29 wells were reconstructed and two dimensional modeling of 4 geological sections were done. Three dimensional modeling is used in order to determine the kitchen areas of Darquain reservoirs and hydrocarbon leakage networks in the region. A 3D cube of the region was modeled to quantify hydrocarbon generation history of source rocks. Five depth maps were constructed based on 2D and 3D available seismic data. Five seismic depth maps and 29 wells data were used to construct depth maps of different horizons from Jurassic to Recent successions. Maps of source rock characteristics are prepared according to geochemical analysis of Darquain Well #2 (Zeinalzadeh et al., Under Review).

Lithological information and geological ages of the strata were extracted from well completion reports. Lithology of formations does not show significant changes or clear trends over the area. Lithological maps were reconstructed from average lithology composition in wells (Fig. 2). Absolute ages were designated based on the geologic time scale of Walker et al. (2013). In this study, geothermal gradient was assigned as 27 °C/km according to well completion reports of Darquain field and constant heat flow value was applied through geological time, which is well supported by relative stability, gentle anticlines and absence of major faults in the Abadan Plain. The Easy %Ro kinetic model of vitrinite maturation (Sweeney and Burnham, 1990) and kinetic data of Behar et al. (2002) was used to calculate the gas and oil generation of source rocks.

3.2. Vitrinite reflectance measurements

Vitrinite reflectance (%Ro) is an optical parameter for describing the degree of thermal maturity of sedimentary organic matter. It is measured in incident white light under a photometer microscope. There are standard procedures for vitrinite reflectance measurements (Suárez-Ruiz et al., 2012a, 2012b; Taylor et al., 1998).

In this study, 24 samples from source rock zones were selected for vitrinite reflectance measurement based on organic richness from Jurassic through Paleogene strata. Chips of rock samples contain kerogen were set into epoxy resin blocks. After hardening, the samples were polished using abrasive papers, alumina powders, diamond paste and lubricant. Vitrinite Reflectance measurements were undertaken using standard reflected light microscopy (Lietz MPV-SP) at RIPI. The light reflected by organic matter in a polished surface is measured under oil immersion (ne 1.518) by a photometer. Vitrinite Reflectance was used for maturity evaluation of source rock samples, determination of Ro-depth trends and calibration of calculated maturity in thermal modeling.

4. Source rock definition

There are several source rock zones in the Darquain field (Table 1 and Fig. 2). Excellent source zones are in the Najmeh (Late Jurassic) and upper part of Sargelu Formations with average TOC of 6.5% at present time. Also, there are good source zones in the lower part of Sargelu and Neyriz (Early Jurassic) Formations. The lower part of the Garau Formation is an excellent source zone (Average 4.2% TOC and 76 m thickness). The Albian Kazhdumi Formation is another very good source zone (72 m with 2.4% TOC). For basin modeling, initial TOCs in past geological time were calculated using method of Peters et al. (2005), assuming an initial HI of 660 mg/g TOC.

Kerogen type II was selected for Kazhdumi, Garau, Sargelu and Neyriz source rocks as it determined by Zeinalzadeh et al. (Under Review). Also, This kerogen type was used in other drill-sites nearby such as South Iraq by Abeed et al. (2013), Dezful Embayment by Bordenave and Hegre (2010) and Kuwait (Derks et al., 2012).

5. Results

5.1. Organic petrography

Vitrinite reflectance values show organic maturity of samples (Table 2) and the mean values increases gradually with depth, from 0.61 to 1.62% Ro. Based on reflectance data from Paleocene and Late Cretaceous succession, maturity stage of early oil generation was obtained for Pabdeh, Ilam and Sarvak Formations (rages from 0.61 to 0.64% Ro). Organic maturity of Kazhdumi source rock (Albian age) is 0.67–0.87% Ro which indicate this source rock is at the peak of oil generation window. End of oil generation maturity stage (organic maturity about 1.04% Ro) was determined for the Early Cretaceous Garau source rock. Jurassic samples (include Sargelu source) are in mature stage of gas or end of oil generation and vitrinite reflectance values range from 1.04 to 1.62% Ro (Table 2).

5.2. Burial history reconstruction and thermal modeling

Vitrinite reflectance data were used to calibrate thermal modeling, and a good fit was obtained between modeling results and measured maturity data (Fig. 3). It was not necessary to assume

Table 1
Source rocks characteristics of Darquain field (Zeinalzadeh et al. (Under Review)).

Source rock	Thickness (m)	Initial TOC (wt.%)	Max. of TOC (wt.%)	Mean TOC (wt.%)
Kazhdumi	72	3	3.87	2.3
Lower Garau	55	7	14.30	4.2
Upper Sargelu	76	14	13.40	6.5
Neyriz	58	5	3.80	2.1

Table 2
Vitrinite reflectance data of the studied samples.

Formation	Depth (m)	Mean Ro%	Maximum Ro%	Minimum Ro%	Standard deviation	Variance	Number of measurements
Pabdeh	2224	0.61	0.75	0.51	0.07	0.005	10
Ilam	2766	0.59	0.59	0.59			1
Sarvak	2778	0.64	0.94	0.45	0.16	0.025	8
Kazhdumi	3422	0.69	0.81	0.53	0.09	0.008	10
Kazhdumi	3430	0.67	0.99	0.52	0.21	0.043	6
Kazhdumi	3436	0.71	0.87	0.58	0.09	0.008	10
Kazhdumi	3440	0.76	0.97	0.51	0.17	0.028	10
Kazhdumi	3444	0.81	1.03	0.56	0.16	0.027	10
Kazhdumi	3450	0.77	0.99	0.55	0.13	0.017	17
Kazhdumi	3458	0.79	0.91	0.64	0.12	0.014	4
Kazhdumi	3460	0.82	0.97	0.63	0.14	0.021	4
Kazhdumi	3470	0.80	1.10	0.65	0.10	0.011	16
Kazhdumi	3474	0.87	0.99	0.67	0.13	0.018	6
Garau	4920	1.02	1.25	0.81	0.13	0.017	15
Garau	4930	1.07	1.26	0.88	0.13	0.018	17
Gotnia	4940	1.24	1.24	1.23	0.01	0.000	2
Gotnia	5100	1.11	1.40	1.00	0.12	0.015	10
Gotnia	5140	1.14	1.38	0.86	0.18	0.033	8
Sargelu	5170	1.14	1.29	0.89	0.14	0.021	11
Sargelu	5175	1.04	1.44	0.82	0.15	0.024	13
Sargelu	5180	1.62	1.74	1.41	0.13	0.017	10
Sargelu	5190	1.04	1.49	0.70	0.25	0.061	11
Sargelu	5195	1.19	1.46	0.87	0.17	0.030	10
Mus	5400	1.22	1.61	0.98	0.20	0.042	7

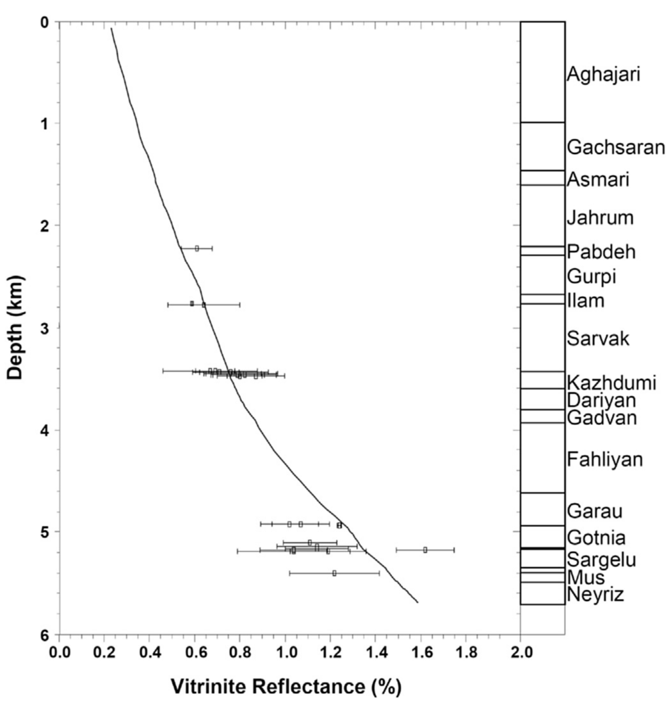

Fig. 3. Maturity profiles of modeling and vitrinite measurements.

erosion or high heat flow events in thermal modeling, because measured temperature data and present day burial depth are sufficient to reach maturity of organic matter to vitrinite reflectance data. There have been several non-depositional events in this region, and computed and measured Ro-depth trends indicate erosion thicknesses were less than 100 m.

The intervals are in deepest burial and maximum temperature at present time as seen in southern Mesopotamian Basin (Abeed et al., 2013). Source rocks temperatures are in a range between 131 (in Kazhdumi) and 177 °C (in Neyriz), and 160 and 170 °C in Garau and Sargelu, respectively. The deepest Jurassic Sargelu and Neyriz source rocks were in oil generation window in Early Cretaceous time (about 130 Ma) when they reached to the depth of 3.4 and 3.7 km respectively (Figs. 4 and 5). Main oil expulsions from the Jurassic sources occurred during Late Cretaceous time. They have been in gas generation and expulsion from Oligocene to recent (Fig. 6). At present, maturity of Sargelu and Neyriz formations are more than 1.3% Ro at the depths of 5.2 and 5.6 km respectively (Figs. 4 and 5); therefore they are at the stage of gas generation and expulsion as stated above.

Garau reached to the oil window in Early Cretaceous time (about 110 Ma) and the hydrocarbon expulsion occurred from Late Cretaceous (95 Ma) up to Oligocene time. It seems that this interval is at the end of oil generation and onset of the gas stage (maturity about 1.2% Ro and 4.75 km burial depth) in Darquain Well #2 (Figs. 5 and 6). The Early Cretaceous Kazhdumi source rock reached to oil window generation (maturity about 0.5% Ro) from Paleocene (Fig. 5). Kazhdumi hydrocarbon expulsion has occurred from Miocene time (20 Ma) (Fig. 6).

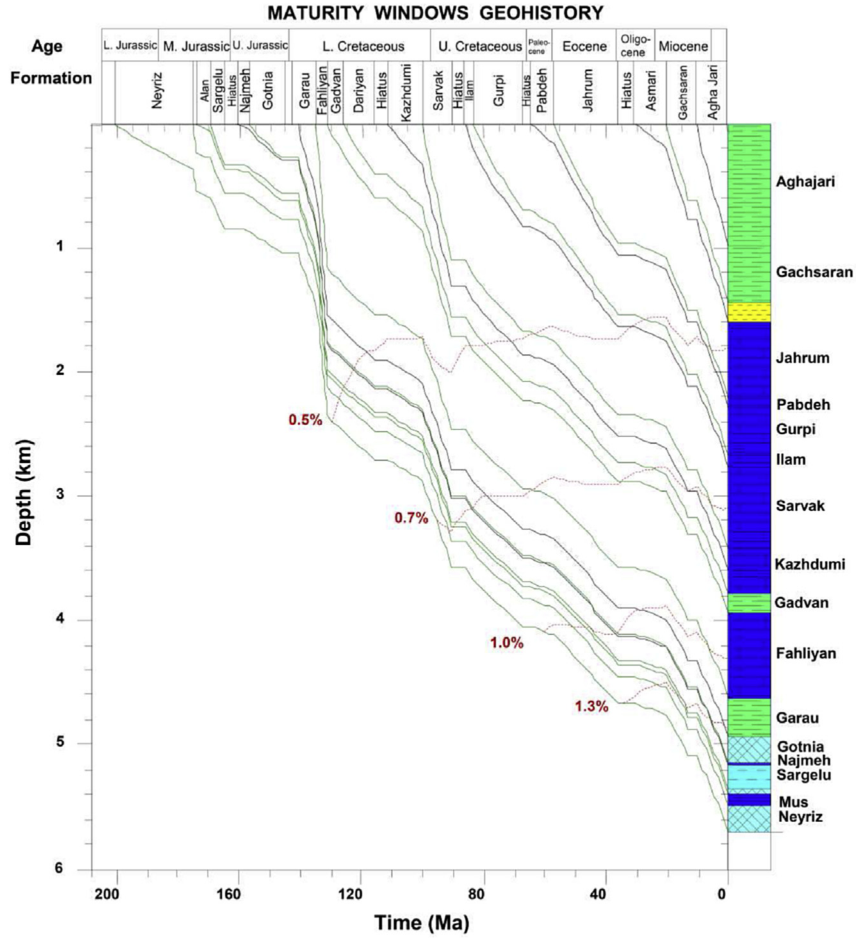

Fig. 4. Burial history of Well Darquain well #2.

Two and three dimensional basin modeling of Darquain anticline show that the quantity of the hydrocarbon originated from Garau and Sargelu source rocks exceeded the capacity of Early Cretaceous (Fahliyan) and Jurassic (Najmeh) reservoirs, respectively. After traps were filled, excess hydrocarbon migrated laterally out of the kitchen area through reservoirs spill points (Fig. 7). Hydrocarbon kitchen areas of Darquain reservoirs extended toward NE where source rocks were buried 900 m deeper than Darquain anticline. Because of thickness variation of Neogene sediments (Agha Jari and Gachsaran Formations) over the kitchen area, Source rocks are in more advanced stages of hydrocarbon generation in deeper settings than shallower part of anticline.

Regional flow patterns of hydrocarbon in Najmeh and Fahliyan Formations were toward the N and NE in about 16.2 Ma (Figs. 8a and Fig. 9a). Migration paths in region shifted toward SW from about 11 Ma, as a result of the deposition of the thick Neogene sediment in the NE of the kitchen area and changes in the regio'nal structural dip (Figs. 8b and 9b). This pattern of migration is consistent with hydrocarbon flow in Mesopotamian Basin of Iraq (Pitman et al., 2004).

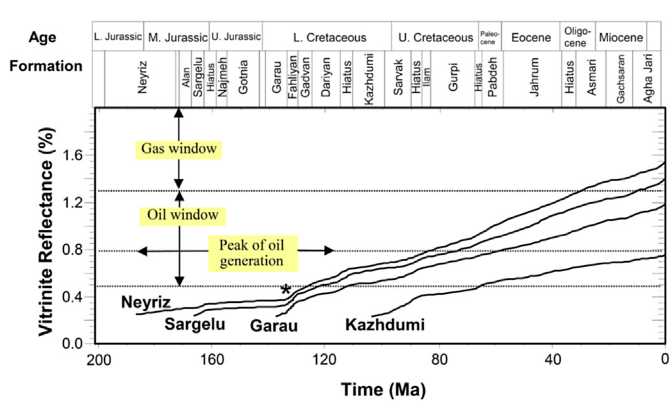

Fig. 5. Source rocks maturity history in Darquain well #2 (* higher rate of maturation).

6. Discussion

The constructed burial history of wells drilled in Darquain anticline indicate high rate of carbonate sedimentation during deposition of the Fahliyan Formation for a short period of time from 134.8 to 131 Ma resulted in faster maturation of the underling source rocks (Figs. 4 and 5). Bordenave and Hegre (2005) have addressed similar issues, high rate of carbonate sedimentation occurred during deposition of Sarvak Formation from 100 to 90 Ma prior to pre Maastrichtian orogenic phase In the Dezful Embayment. High rate of sedimentation could be related to crustal thinning and rifting, which associated with high paleo heat flow (Baur et al., 2010) that could causes higher maturity of source rocks. While measured maturity of strata bellower Fahliyan Formation is slightly less than calculated maturity, by considering constant heat

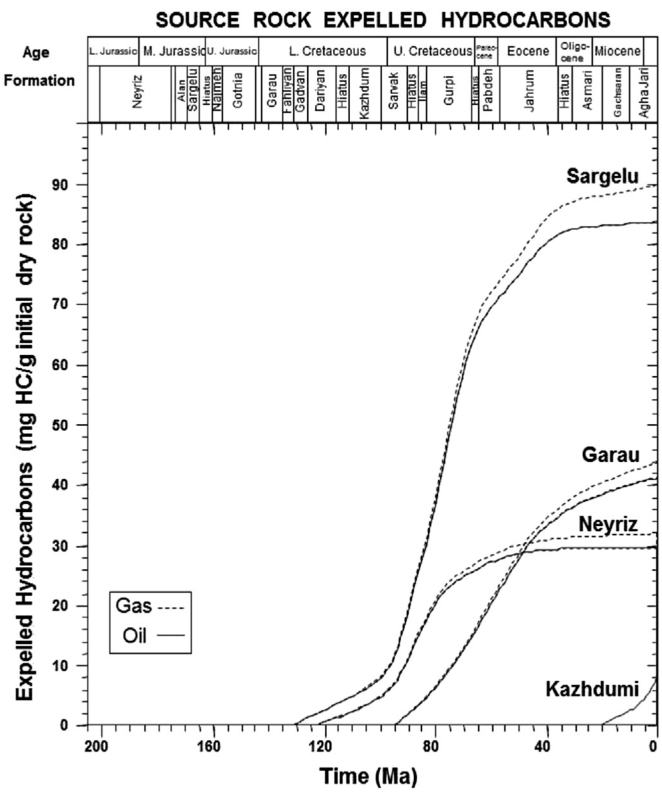

Fig. 6. Source rocks hydrocarbon expulsion history in Well Darquain #2.

flow. In other words, measured vitrinite reflectance does not support high heat flow during deposition of Fahliyan Formation and high sedimentation rate is not related to crustal thinning and rifting. It could be related to instability of Arabian Platform. Although considering constant heat flow through geologic time is known as oversimplification, but in several modeling studies in the region appropriate fit between modeling results and geochemistry parameters with constant heat flow were obtained (Abeed et al., 2013; Bordenave and Hegre, 2005; Opera et al., 2013; Rudkiewicz et al., 2007).

In NE of kitchen area there was high rate of sedimentation during Neogene time (Agha Jari and Gachsaran Formations) contemporary with the Zagros Orogeny. Neogene sediments had a significant impact on hydrocarbon generation of Kazhdumi Formation in NE of kitchen area where quantity of Kazhdumi hydrocarbon expulsion is two times more than anticline setting. While Garau and older source rocks passed peak of oil generation a long time before Neogene, Kazhdumi source is at end of oil generation peak in deepest part in the NE, and it is at oil generation peak in Darquain anticline.

Among source rock intervals in the study area, the Sargelu and Garau Formations are the main sources of the Jurassic and Cretaceous petroleum systems which are separated by Gotnia Formation. Geochemical results from the Sargelu and Garau source rocks in the Zagros Basin have shown close similarities and have not been found obvious differences in carbon isotope and biomarker between these two units (Ashkan, 2004). Similar situation is present in the Jurassic (Najmeh –Sargelu) and Cretaceous (Sulaiy) source rocks in Kuwait (Abdullah and Connan, 2002; Kaufman et al., 2002). Gotnia Formation consists of about 84 m of salt layers and the same thickness of anhydrite. Ductile behavior of Gotnia keeps overpressure under this layer in the Darquain field as well as in some parts of the Kuwait and Iraq (Abeed et al., 2013; Ali, 1994) and it is unfaulted seal in southern Mesopotamian Basin (Abeed et al., 2013). While Fahliyan reservoir contains mainly liquid phase, there are gas and condensate reservoirs underling the Gotnia Formation. So the Gotnia seal probably prevented migration of gas from underling toward upper reservoirs.

Hydrocarbon expulsion from Sargelu and Garau sources and traps formation occurred contemporaneously, during the Late Cretaceous time (Fig. 10). It seems that first Najmeh Formation is fed by liquid hydrocarbon then oil replaced by gas during the Cenozoic. In both Jurassic and Cretaceous petroleum systems, reserve overlay source rock and expelled hydrocarbons from source rocks migrated upward into younger reservoir layers. Jurassic gas reserve is limited above and below by thick evaporitic layers, Gotnia and Neyriz- Alan Formations, respectively. As basin modeling shows, lateral migration through Najmeh has been occurred toward SW but this reservoir has only 17 m thickness and high pore pressure so it is an isolated interval. Some parts of the oil generated inside Sargelu could be cracked in situ into pyro bitumen and gas as reported in some parts of Zagros region (Bordenave and Hegre, 2010).

Fahliyan reserve is limited above by Gadvan shale and below by

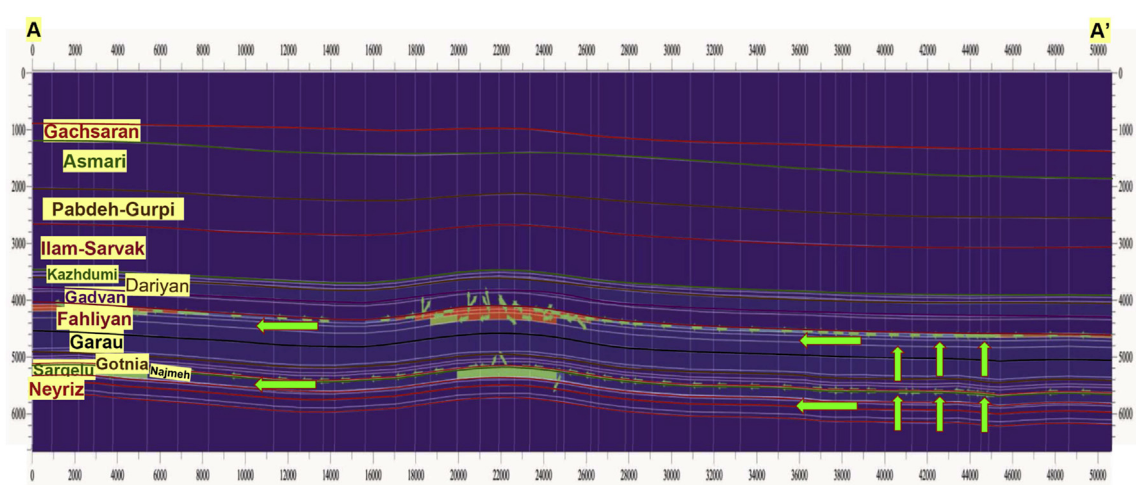

Fig. 7. Migration paths in two-dimensional section (see Fig. 8b for location of section). Expelled hydrocarbons migrated vertically to reservoir rocks and lateral migration occurs through reservoirs.

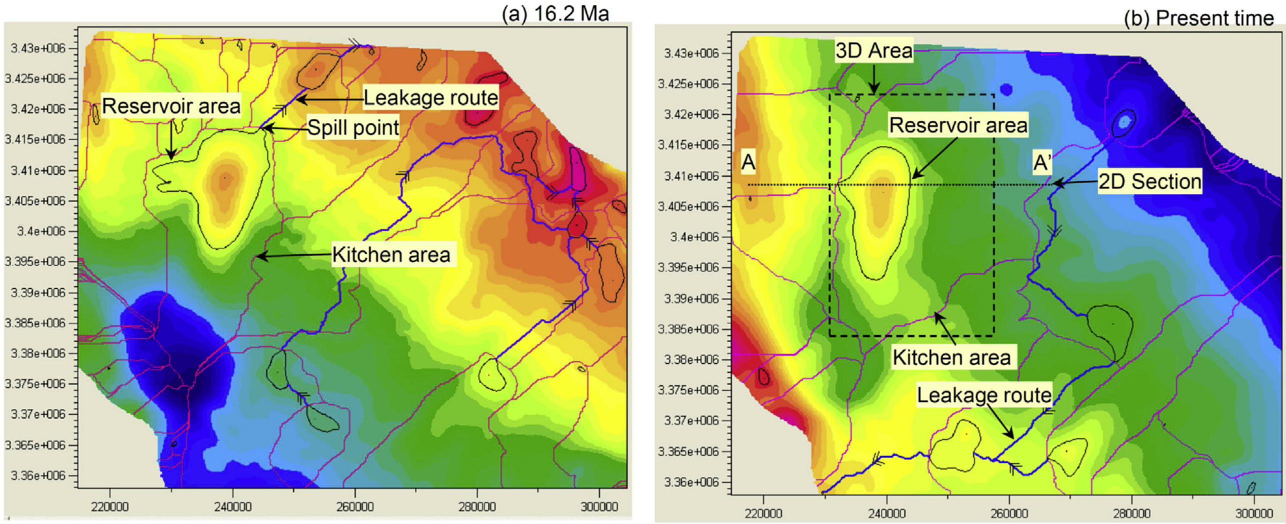

Fig. 8. Modeled Cretaceous (top Fahliyan) kitchen area in Darquain and adjacent area at time periods: (a) 16.2 Ma and (b) Present time. Kitchen area (red line), leakage routes (blue line), reservoir area (Black line) and spill point were shown in maps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

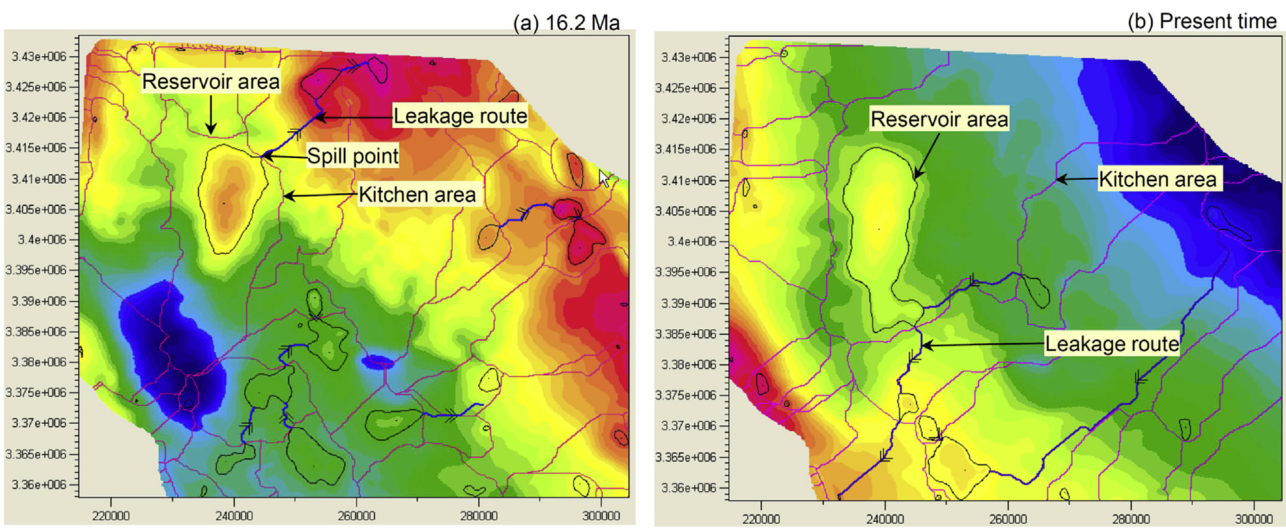

Fig. 9. Modeled Jurassic (top Najmeh) kitchen area in Darquain and adjacent area at time periods: (a) 16.2 Ma and (b) Present time. Kitchen area (red line), leakage routes (blue line), reservoir area (Black line) and spill point were shown in maps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

evaporitic sediments of the Gotnia that prevent downward migration of hydrocarbon. Basin modeling shows lateral migration through Fahliyan reservoir (about 400 m thickens) toward anticline and after filling the tarp, migration was toward west (Fig. 7).

Hydrocarbon expelled from Kazhdumi source rock could migrated directly into the Ilam Formation in above. Ilam is minor reservoir may be due to lack of suitable closure. Toward Kuwait and south Iraq, Kazhdumi facies change to porous sandstone and it is in shallower depth. Hydrocarbon migration paths were obtained from basin modeling support lateral migration toward SW through Kazhdumi sandy sublayers.

7. Conclusions

Source rocks of the Jurassic petroleum system, Sargelu and Neyriz Formations, are in gas generation window and they passed main oil generation phase prior to Cenozoic. These source rocks charged Jurassic Najmeh/Sargelu Gas reservoirs in the Darquain anticline. Cretaceous petroleum system has been charged by the Early Cretaceous Garau source rock which it was in hydrocarbon expulsion at the end of Cretaceous time when trap structure formed and charged the Fahliyan reservoir. The Garau source is at the beginning of gas expulsion and end of oil expulsion. The Kazhdumi hydrocarbon expulsion has occurred from Miocene and it is at the peak of oil generation at present time and hydrocarbon could migrate directly from this source into the Ilam Formation.

Jurassic gas and Cretaceous oil reservoirs were directly charged by source rocks in theirs kitchen area. The gas from Jurassic source rocks accumulated in Najmeh and did not reach to Cretaceous Fahliyan reservoir. It seems Gotnia Formation separated the Jurassic reservoirs from Cretaceous reservoirs. Hydrocarbon migrated laterally through reservoirs toward anticline and after trap filled hydrocarbon overflow migrated out of the kitchen area. Thick deposits of the Neogene sediments in the NE of the kitchen area and

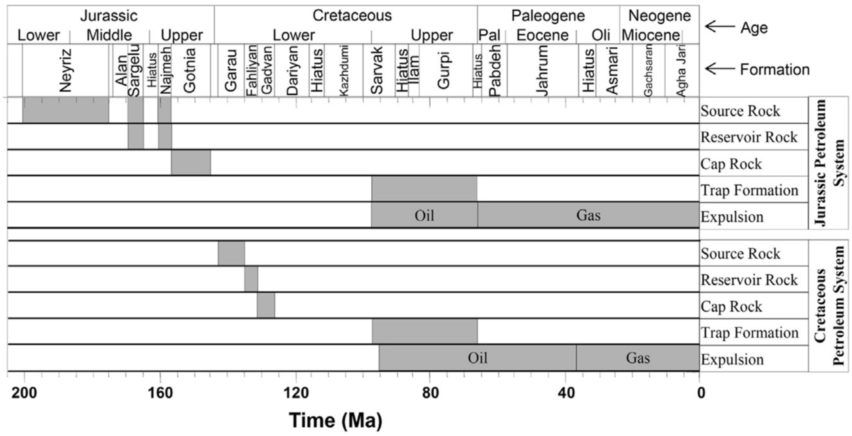

Fig. 10. Events chart of Cretaceous and Jurassic petroleum systems.

structural dip change from Zagros Orogeny caused hydrocarbon migration paths in area to shift from NE to SW direction about 11 Ma. Modeling indicates that the quantity of hydrocarbons generated in the Darquain kitchen area is more than capacity of reservoirs; therefore excess hydrocarbon has migrated laterally toward west and south west through reservoirs.

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